NUMERICAL SIMULATION OF LOCOMOTIVE FIRES IN THE LYON-TURIN TUNNEL

Emmanuel RUFFIN, André CARRAU, Claude CWIKLINSKI
Institut National de l'Environnement industriel et des Risques, INERIS, France

ABSTRACT

Among the ventilation studies for the tunnel of the Lyon-Turin project, located between St Jean de Maurienne in France and Susa in Italy, a particular work has been devoted to locomotive fires and smoke propagation. The purpose of this study was to bring information on the outcome ambient conditions for passengers during a locomotive fire and to confirm the ventilation strategy worked out by Alpetunnel who is in charge of the project. Furthermore the study has been focused on the thermo-aeraulic and physicochemical conditions in the tunnel during a rear locomotive fire. For that INERIS has adopted a deterministic point of view based on lessons issued from the past and results of research projects like Eureka Firetun Project. This study is divided into three parts : bibliography and search for data on materials and locomotives fires, calculation of few probable fires with various possible ignition locations and simulation of the combustion products propagation for the two most probable fire scenarios. Results show that the escape conditions in the tunnel during the fires are acceptable for the two studied scenarios.

1. INTRODUCTION

Generally rail tunnels are not the cause of accidents except when the loss of their structures' integrity is the cause. In fact, the major risk in tunnel is due to the possibility of effects aggravation induced by the enclosed space. Among the possible accidents, fires can induce very problematic evacuation situations and a lot of difficulties for the rescue access and operations.

All over the world, important accidents have occurred, with or without victims and they widely justify the research projects such as EUREKA FIRETUN 499 (1) or MEMORIAL TUNNEL (2).

Concerning rail tunnels, fires are frequently rolling-stocks fires. Many studies have been conducted on coach fires but few results are published on locomotive fires and their consequences (3). It is true that locomotives have often got security systems for fire detection and extinction and then consequences of these fires are generally reduced to incidents causing only little harm. Nevertheless a fully developed locomotive fire can alter the mobility of a

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train and therefore the consequences have to be studied as one of the major scenarios for the safety in rail tunnels.

2. LOCOMOTIVE FIRE MODELLING

This study is based on characteristics of a TGV's locomotive type. As a first hypothesis we consider that a fire ignites in the rear-locomotive and the train has to stop in the tunnel. After the train has stopped smokes are convected towards the passenger coach by the ventilation system. Note this direction of propagation is the same than the one induced by the piston effect in the case of a single way tube. In this study we assume that the fire effects have begun when the piston effects have stopped. At this time only the rescue ventilation is working.

Figure 1 schematically shows how the locomotive is filled with flammable materials. The driver's cabin is separated by a fire resisting wall and thus the materials included in it do not participate to the fire.

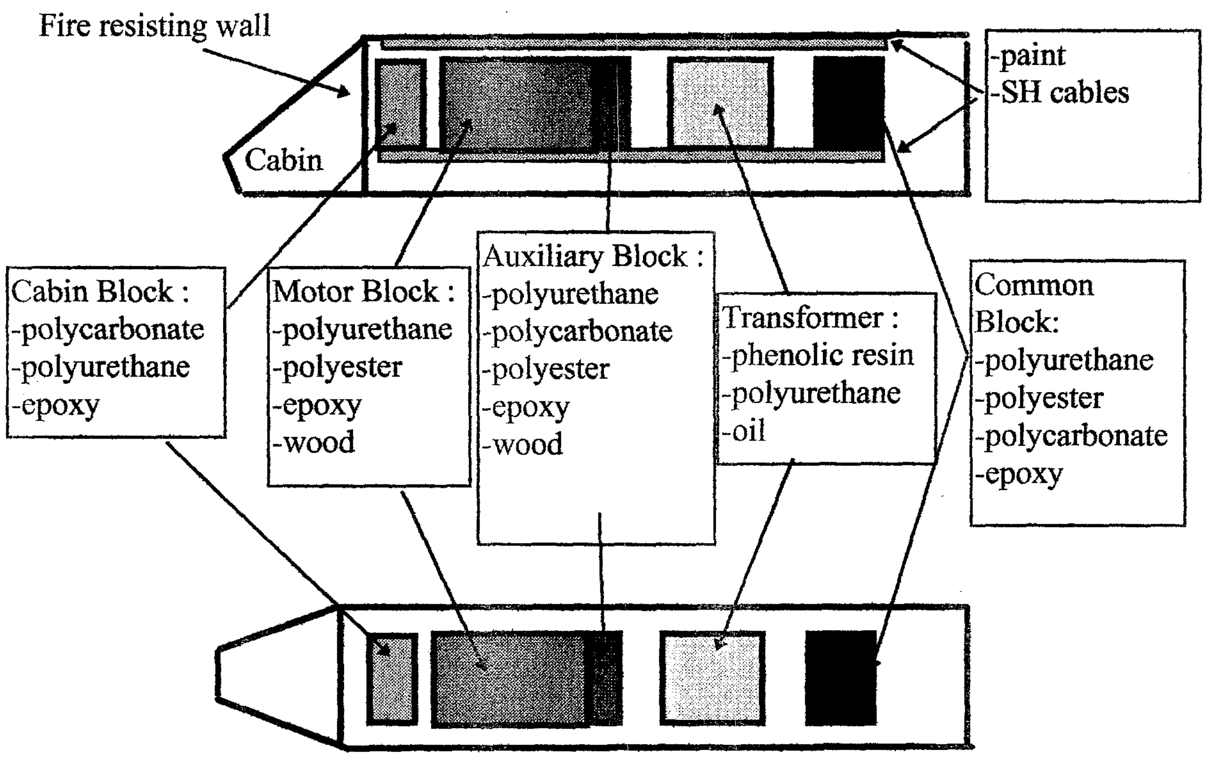

Figure 1 : Distribution of flammable materials.

The materials can be distributed in different ways :

- localised in a defined volume : « box » which can be separated from other empty « boxes »,
- homogeneously distributed along a geometrical space (e.g. cables path),
- applied on walls (e.g. paint film).

The first study step has been devoted to collect the combustible raw material characteristics. Three main materials types can be listed as following :

- Oil (the major part fills up the power transformer) 1000 kg
- Synthetic materials 1750 kg
- Various other materials 750 kg

Total 3500 kg

Precise data have been found on each material and each raw material is characterized by the following main parameters :

- Space distribution and geometry
- Combustion heat ....MJ
- Yield of combustion product (Y)..g/g
- Radiative heat over Convective heat ratio.....................................%
- Burning rate..g/m2/s
- Self-ignition temperature (SIT) ....°C

For example the data collected for the oil and the polyurethane was :

	Oil	**Polyurethane**
ΔH_c (kJ/g)	*43.1*	*25*
Y CO_2 (g/g)	*2.64*	*1.53*
Y CO (g/g)	*0.019*	*0.04*
Y Soot (g/g)	*0.059*	*0.125*
Y HCN (g/g)	-	*0.011*
H chem. (kJ/g)	*36.9*	*15.9*
H rad. (kJ/g)	*12.4*	*8.8*
H conv. (kJ/g)	*24.5*	*7.1*
Burning rate ($g/m^2/s$)	*39*	*22*
SIT (°C)	-	*415*

Table 1 : Main combustion characteristics of two typical flammable materials (5, 6, 7).

The fire modelling needs an homogeneous approach in regards of the various and complex chemical and physical processes. In the case of a locomotive fire in a tunnel we have to evaluate, on the basis of an ignition scenario, the temporal and spatial propagation of the fire into the locomotive. Furthermore we have to define the combustion products which leave the locomotive during the fire. This work has been made with the zone code MAGIC[1] by Sechaud & Metz, on the basis of the data collected by INERIS for the flammable materials and their locations and distributions into the locomotive.

This code takes into account the following time variable parameters :

- walls and gases temperatures into the locomotive,
- height of the hot zone[2],
- thermal fluxes received by the flammable material,
- self-ignition of a flammable material if its self-ignition temperature is reached,

[1] MAGIC is a zone model developed by Electricité de France.
[2] In a zone code two layers are considered : the hot and the cold layer.

- wall or roof fusion/consumption,

and then

- propagation of the fire in the locomotive,
- multi-fire locations...

The studied scenarios have been choiced, in one hand, because the knowledge of motor block ignition in the past, and in an other hand, the potential gravity of an ignition of the oil's transformer.

These scenarios have been studied for two ventilation levels in the tunnel, 3m/s or 6m/s of bulk velocity.

Results give the temporal variation of the fire locomotive source terms which include the wall temperature of the locomotive and the chemical and physical properties of the combustion products by the way of the following parameters : locomotive walls temperature, smoke mass flow, unburned mass flow, and concentrations of CO_2, CO, CH, HCN, O_2 in the smoke flow.

3. FIRE SOURCE TERMS AND PROPAGATION FIELD GEOMETRY

The results of the fire propagation scenarios into the locomotive have been used in our unsteady smoke propagation in the tunnel by the way of boundary conditions given on four geometrical zones of the locomotive. Then source terms are the following :

- a fresh air admission in the locomotive from the tunnel,
- a smoke release from the locomotive in the tunnel,
- the apparition of a new opening due to the combustion or fusion of a material through which air may enter or smoke be released.

The most probable scenarios indicate that possible exchange surfaces are the following :

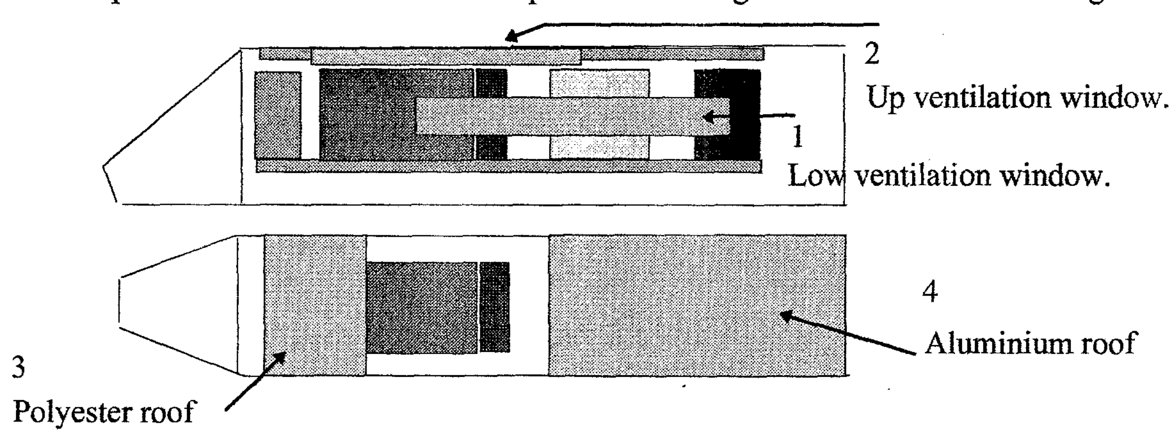

Figure 2 : Possible openings for smoke convection (pre-existing and due to melting).

Source terms are set on these four surfaces during the simulation by giving,

- in case of a fresh air entrance, the mass flow
- and, in case of a smoke release, the emission velocity, the smoke temperature and the CO_2 concentration.

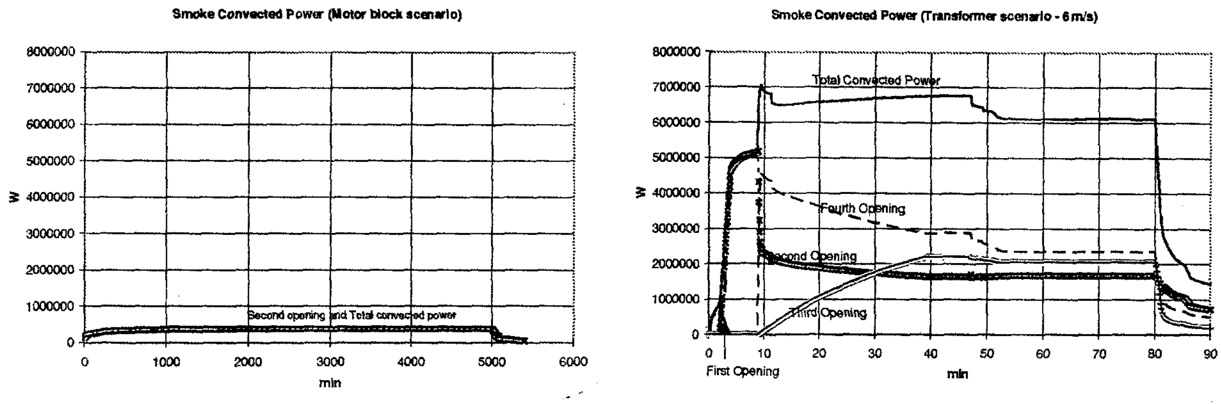

Figure 3 : Convected power source terms (see figure 2 for the openings definition).

The wall temperature of the locomotive is also given by the zone code at each time step in order to take into account to the heat induced by the locomotive in the tunnel.

Four scenarios have been kept for the smoke propagation simulation : motor block - 3m/s and 6m/s ; transformer - 3m/s and 6m/s. As only a small difference has been found for the fire locomotive power between the 3m/s ventilation rate and the 6m/s one, the study cases can be resumed in two major cases : a motor block fire which produces around 0.35 MW of convected power and an oil pool fire which can produce up to 7 MW of convected power in the tunnel. Note that the fire power is divided into two parts : the radiative part which is absorbed by the locomotive itself and participates to the elevation of its walls and structures temperature, and the convected part which is released in the tunnel through the openings. The ratio of radiative power to the total power is about fifty percent on an average but can significantly vary with each combustible material.

The propagation smoke geometry is the following :

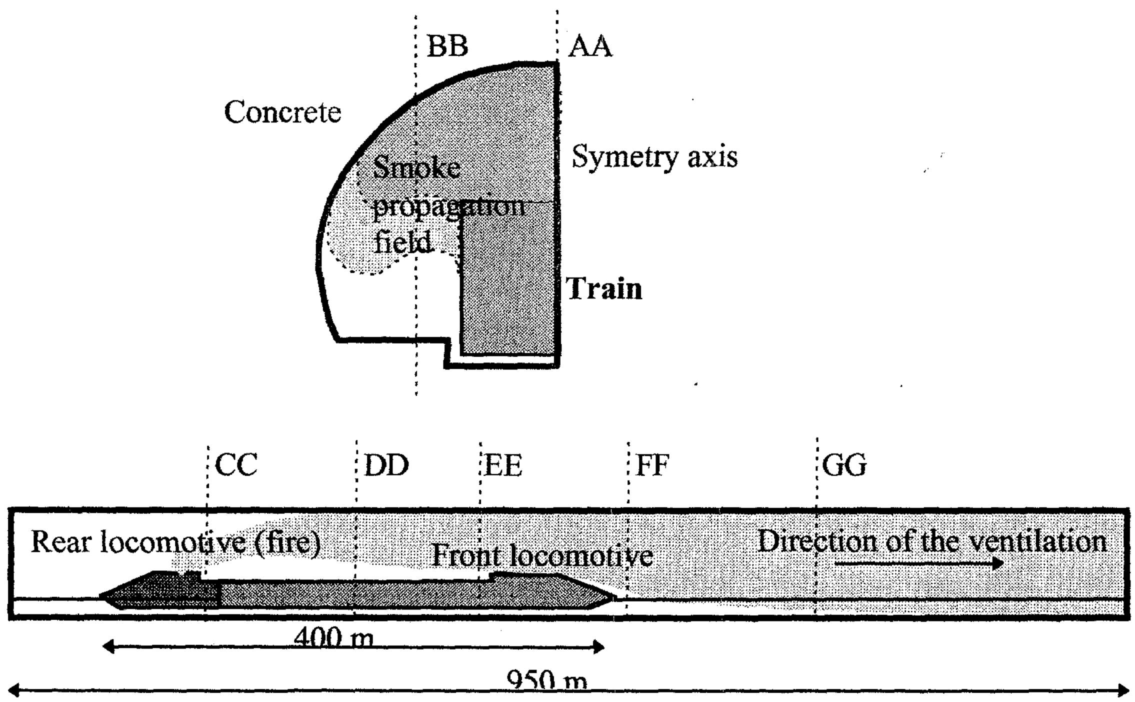

Figure 4 : Simulated smoke propagation field.

4. NUMERICAL RESOLUTION

Simulations were done assuming that the train has stopped before the fire growth and at this time piston effects had vanished. So the unsteady flow field is related to the unsteady boundary conditions of the fire sources terms. The flow is calculated with Phoenics TM[3] by resolving the mean turbulent Navier-Stokes equations and the perfect gas law. The well-known general form of the transport equations is :

$$\frac{\partial(\rho\phi)}{\partial t} + div(\rho V\phi) - div(\Gamma_\phi grad\,\phi) = S_\phi \tag{1}$$

where ϕ is a transported massic variable.

In this study the following variables are solved : the mass, the momentum in a three-D space geometry, the energy, the smoke concentration, the turbulent kinetic energy and its dissipation.

For convective momentum and heat transfer to the walls, the friction has been modeled with wall functions and fitted (by the way of the mean height roughness) in order to respect the given friction coefficient level. Considering the Reynolds Analogy hypothesis this procedure ensures also quite correct heat fluxes. In our simulation only the forced convective heat transfer has been modeled, the free convective heat transfer appearing to be small in our study cases.

For radiative heat transfer a simple model has been applied only for the walls/gas heat transfer assuming that the smokes were very thick. This choice was justified by the fact that source materials filling the locomotive can produce dense smokes (transformer oil). In this case the wall radiative transfers are assumed to be present in a small region near the wall. Numerically, the radiative transfer was applied only on the first fluid cell near the walls with the following equation :

$$Q = 1.\,\sigma(T^4_{fluid} - T^4_{wall}) \tag{2}$$

where 1 is the smoke emissivity and σ the Stefan-Boltzman constant.

5. RESULTS

First scenario : Motor block fire (0.35 MW)

Source terms indicate that ratios between CO_2 and the other combustion products are quite constant during this fire. As the CO_2 concentration is calculated in the whole geometry it was easy to estimate the possible effects of combustible products on passengers during the evacuation. In such a situation the most relevant parameters are, at least, temperature, toxicity, and visibility. This last parameter is very important due to the rapid increase of the emergency difficulties when visibility decreases.

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[3] Phoenics is a computer code for solve three dimensionnal Navier-Stokes equations. This code is developped by CHAM.

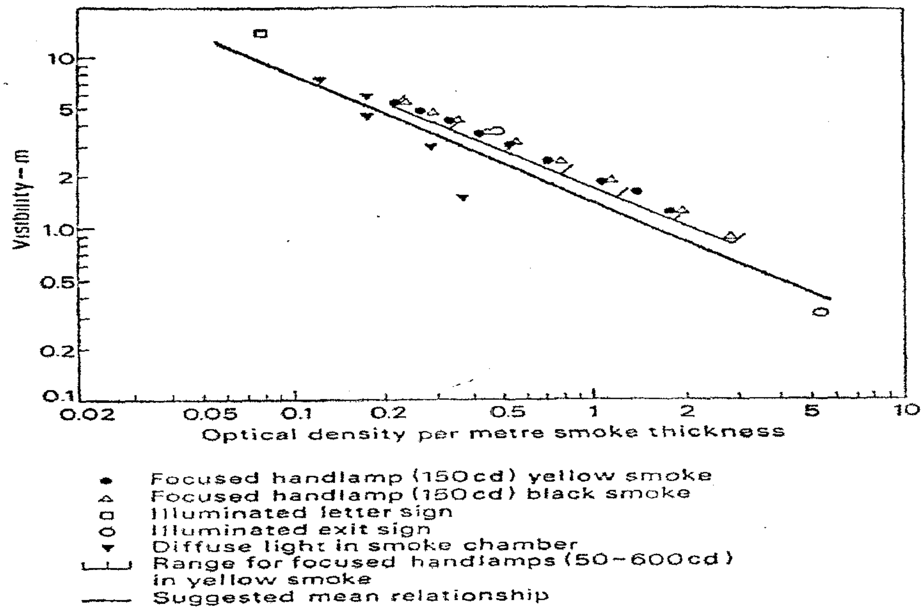

Figure 5 : Relationship between visibility and optical density of smoke from fires (9).

To evaluate this parameter we have used the methodology elaborated during the EUREKA FIRETUN 499 project (8) : the visibility is calculated on the basis of an empirical formula for the Optical Density (O.D.). This formula gives us a relation between the Optical Density, the CO_2 volumic concentration and the temperature at the considered point. In our study case the empirical constant k is given by the heptane FIRETUN experiments. Furthermore the visibility is related to the optical density by curve in figure 5. To establish our visibility calculation we have considered thesuggested mean relationship for the various light sources.

For all parameters results show acceptable conditions of evacuation for both ventilation rates. The following results are given at 1.6 m heigth in the evacuation zone, along the train and after the train on 800 m long. The maximum values are logically reached for the 3m/s ventilation case:

- *maximum temperature elevation :* < 3 °C
- *maximum concentration elevations :* < 300 ppm CO_2, < 9 ppm CO, < 1 ppm HCN
- *minimum visibility :* > 10 m

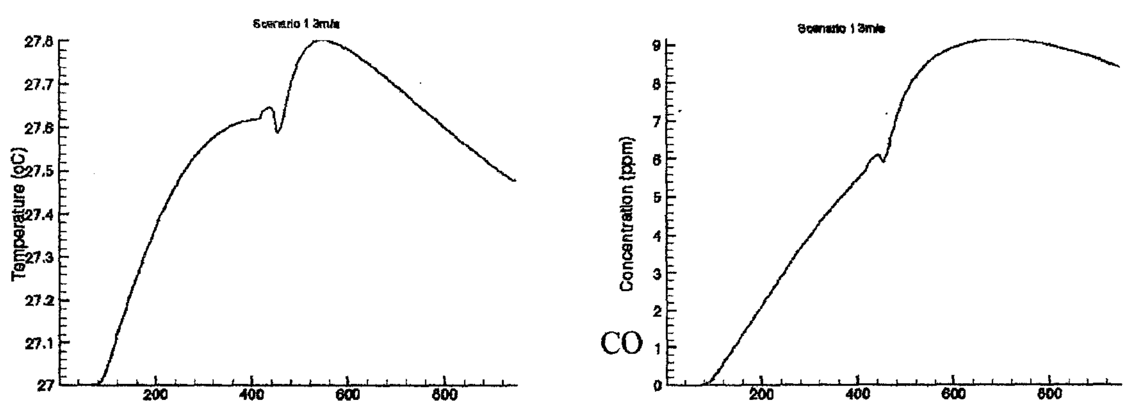

Figure 6 : Results for the Motor block 2 scenario.

Second scenario : Transformer fire (7 MW)

In this case, ratio between CO_2 and other combustion products are also constant except during the first ten minutes because of the rapid combustion of synthetic materials producing HCN. The maximum temperature elevation (reached in the various simulations) does not exceed 44 °C. But, during the first ten minutes toxicity and opacity peaks occur due to the high combustion rate and the PE-Roof consumption.

- maximum concentration elevations :	*< 8000 ppm CO_2, < 250 ppm CO, < 8 ppm HCN*
- visibility :	*2 m < visibility < 10 m*

After this toxicity peak concentrations and visibility are the following :

- maximum concentration elevations :	*< 5500 ppm CO_2, < 170 ppm CO, < 1 ppm HCN*
- visibility :	*3 m < visibility < 10 m*

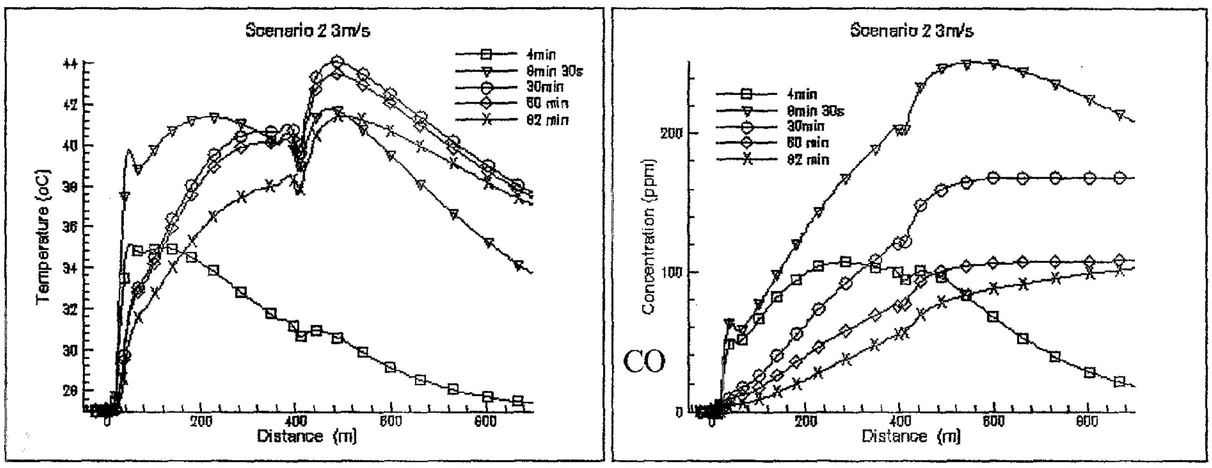

Figure 7 : Results for the Power Transformer scenario.

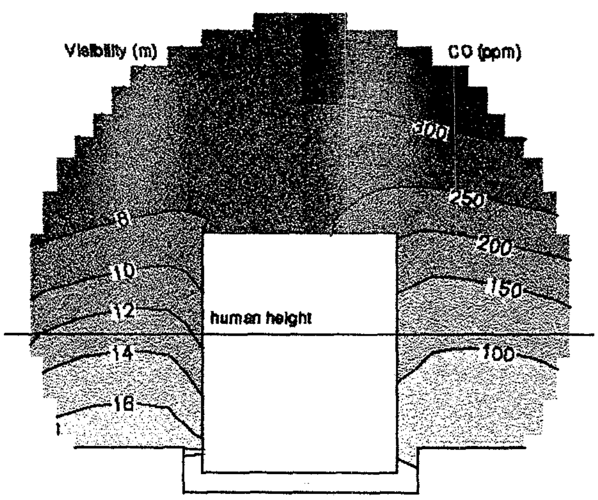

Figure 8 : Ambient conditions in the DD section.
(Power Transformer scenario)

Note that for all parameters reached values are about twice less in the 6m/s ventilation case than in the 3m/s ventilation case, the flow geometry being unchanged. The flow geometry along the train is a stratified hot layer flow for the two ventilation levels. No back-layering has been found, the bulk velocity being larger than the critical velocity. This is confirmed by the analytical study of the critical velocity. Visibility and CO concentration distributions in the DD section are given in the figure 8. Along the train (figure 9) the concentration and temperature vary slowly due to the calm distratification of the hot layer. After the front locomotive the hot layer brakes itself because of the nozzle disturbance.

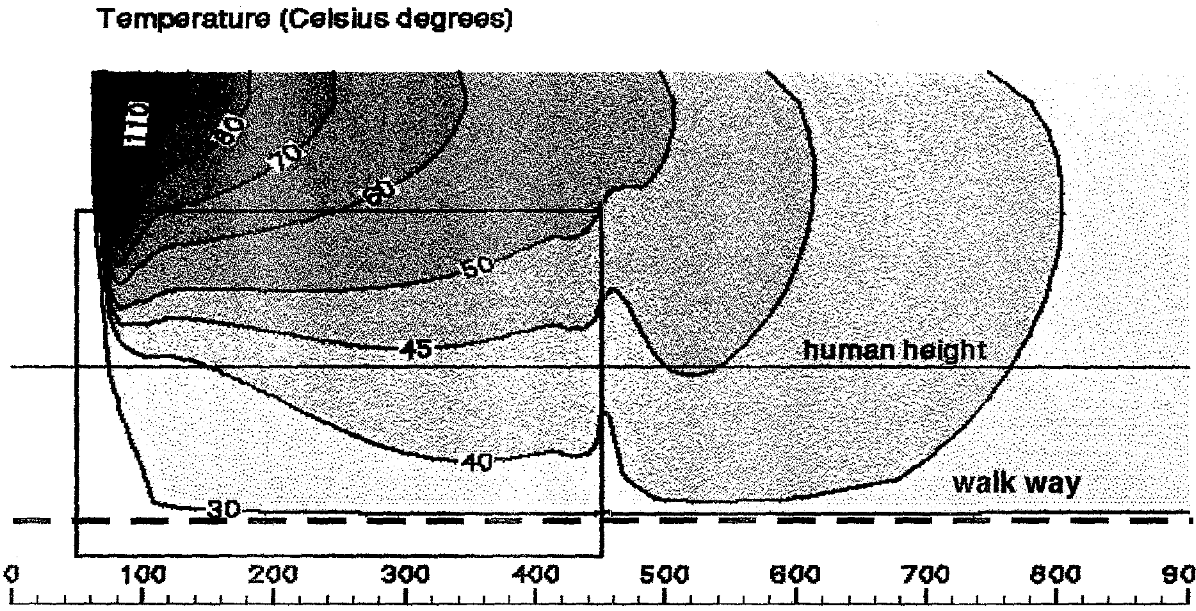

Figure 9 : Ambient *conditions along the train in the BB section.*
(Power Transformer scenario)

6. CONCLUSIONS

For the two studied scenarios the evacuation outcome conditions are reasonably acceptable especially for the 6m/s ventilation rate.

The maximum values listed above are reached behind the train when the nose of the front locomotive breaks the stratified hot layer. Along the train the air quality slowly varies because the train acts as a protection.

The total collapse and disappearance of the PE-roof (3rd opening) and later of the Aluminum-roof (4th opening) allow smokes to propagate in a hot layer above the train and decreases the smoke releases along the locomotive through the first and second openings.

Temperature is not the relevant parameter in the studied cases but visibility seems to be very important for the evacuation duration.

The toxicity could also be an important parameter because of concentration peaks which can occur during high burning rate moments of synthetic materials.

In long tunnel, piston effects can be present during up to ten or fifteen minutes. During this time period, this effect could destratify a hot layer and could impeach a safe evacuation. But in the same manner if the rescue ventilation strategy is adequate, piston effects can help to dilute the fire power and/or a toxicity peak.

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